Squeezing River Catchments Through Tectonics: Shortening and Erosion across the Indus Valley, NW Himalaya

Citation for published version:
Sinclair, H, Mudd, S, Dingle, L, Hobley, D, Robinson, R & Walcott, R 2017, 'Squeezing River Catchments Through Tectonics: Shortening and Erosion across the Indus Valley, NW Himalaya', *GSA Bulletin*, vol. 129, no. 1-2, pp. 203-217. https://doi.org/10.1130/B31435.1

Digital Object Identifier (DOI):
10.1130/B31435.1

Published In:
GSA Bulletin

Squeezing River Catchments Through Tectonics: Shortening and Erosion across the Indus Valley, NW Himalaya

[1]Sinclair, H. D., [1]Mudd, S. M., [1]Dingle, E., [2]Hobley, D. E. J., [4]Robinson, R., [1,3]Walcott, R..

[1]School of GeoSciences, The University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, UK.

[2]Department of Geological Sciences/CIRES, University of Colorado Boulder, UCB 399, 2200 Colorado Ave., Boulder, CO 80309-0399, USA.

[3]Department of Natural Sciences, National Museums Scotland, Chambers Street, Edinburgh EH1 1JF, UK.

[4]Department of Earth Sciences & Environmental Sciences, Irvine Building, University of St Andrews, St Andrews, KY16 9AL, UK

Abstract

Tectonic deformation of the plan-view form of river networks during crustal shortening has been proposed for a number of mountain ranges. In order for this to occur, the modification of topography across a thrust fault must be retained without being fully countered by subsequent erosion. Quantification of these competing processes and the implications for catchment topography have not previously been demonstrated. Here, we use structural mapping combined with dating of terrace sediments to measure Quaternary shortening across the Indus River valley in Ladakh, NW Himalaya. We demonstrate ~0.25 m kyr^{-1} of horizontal displacement since ca. 38 ka on the Stok Thrust in Ladakh which defines the southwestern margin of the Indus Valley catchment, and is the major backthrust to the Tethyan Himalaya in this region. We use normalised river channel gradients of the tributaries that drain into the Indus River to show that the lateral continuation of the Stok Thrust was active for at least 70 km along strike. Shortening rates combined with fault geometries yield vertical displacement rates which are compared to time-equivalent erosion rates in the hanging wall derived from published detrital ^{10}Be analyses. The results demonstrate that vertical displacement rates across the Stok Thrust were approximately twice that of the time equivalent erosion rates implying a net horizontal displacement of the surface topography, and hence narrowing of the Indus Valley at approximately 0.12 m kyr^{-1}. A fill terrace records debris flow emplacement

linked to thrust activity, resulting in damming of the valley and extensive lake development. Conglomerates beneath some of the modern alluvial fans indicate a northeastward shift of the Indus river channel since ca. 38 ka to its present course against the opposite side of the valley to the Stok Thrust. The structural, geomorphological and sedimentological data are integrated into a model of progressive topographic displacement across the valley concomitant with alluvial aggradation in the valley. This analysis provides an illustration of the tectonic and geomorphic processes involved in the deformation of range-parallel longitudinal valleys in mountain ranges.

1. Introduction

The topography of active mountain ranges records surface uplift in response to crustal thickening countered by erosion (e.g. Dahlen, 1990). The horizontal velocities that drive crustal thickening are commonly an order of magnitude higher than the vertical, and so it is expected that this should be recorded by the topography (Pazzaglia and Brandon, 2001; Willett et al., 2001; Miller and Slingerland, 2006). Model experiments have indicated that the broad asymmetry of many small mountain ranges such as the Southern Alps of New Zealand, the Pyrenees and Taiwan may be explained by the horizontal translation of deforming rock from the side of the range dominated by accretion towards the opposing side (Willett et al., 2001; Sinclair et al., 2005; Hermann and Braun, 2006).

It is reasonable to suggest that such large scale forcing of topography must also play a role in determining the geometry of river catchments and their channel courses. At the largest scale, it is proposed that the extraordinarily elongate form of the rivers draining eastern Tibet (Salween, Mekong and Yangtse) represent highly strained forms of previously more regularly shaped catchments in response to distributed crustal shortening and rotation around the eastern corner of the Indian indentor (Hallet and Molnar, 2001). Similarly, the river catchments of the Southern Alps of New Zealand are understood to have been deformed to their present shape during oblique convergence (Koons, 1995; Castelltort et al., 2012). Tectonically induced changes in catchment shape may be further modified by river capture and progressive migration of drainage divides in response to factors such as variability in rock strength (Bishop, 1995), changing river base-levels (Mudd and Furbish, 2005) and ridge-top glaciation (Dortch et al., 2011a). The competition between tectonic deformation of river catchments and the response of the rivers is highlighted across the Himalaya where all of the big rivers are characterised by steepened reaches and more localised knickzones as they respond to variable rock uplift fields (Seeber and Gornitz, 1983; Wobus et al., 2006a). The smaller river catchments near the foothills of the Himalaya exhibit variable catchment geometries in response to lateral advection over thrust ramps (Champel et al., 2002; Miller et al., 2007). Large-scale catchment deformation has broad implications for the topographic form of active mountain ranges and the distribution of erosion and transported sediment to surrounding sedimentary basins. Any modification of catchment shape also has implications for the scaling of upstream catchment area with channel length and hence the long profile of rivers (Whipple and Tucker, 1999; Willett et al., 2014).

Fluvial erosion can be approximated by a power-law relationship between channel slope and river discharge (Howard et al., 1994; Whipple and Tucker, 1999). In this stream power model, the fault offset generates an oversteepened channel reach (knickpoint or knickzone) that migrates upstream as a kinematic wave. Additionally, the model predicts that sustained differential rock uplift across a fault will generate increased channel steepness (for a given upstream area) on the upthrown block . Analyses of channel steepness has been used to assess fault activity in mountain ranges (e.g. Hodges et al., 2004; Kirby and Whipple, 2012), with relative rock uplift in the hanging wall of a thrust fault leading to increased stream power generated by channel steepening.

Little is known of the interaction between thrust shortening and the consequent deformation of catchment shape as opposed to the offset of individual channels by faults. As yet, there has been no demonstration of the horizontal convergence of drainage divides in response to shortening on a thrust fault that bisects a catchment. In order to do this, both the shortening and the time equivalent erosional response need to be quantified to determine the topographic response.

The objective of this study is to test whether rates of horizontal displacement across a thrust fault are capable of driving the horizontal convergence of opposing drainage divides when moderated by the erosional response to fault displacement. Specifically, we examine the Indus River valley in Ladakh, NW India which is one of the largest longitudinal river catchments of the Himalaya with an average width of around 35 km and a length of approximately 200km parallel to the mountain range. The aim is firstly to test for the presence of active shortening across the Indus Valley, as this has never been demonstrated. This is regionally significant as the valley follows the line of the main backthrust in the region carrying the Tethyan Himalaya northeastwards towards the Gangdese batholith (van Haver, 1984; Searle et al., 1990). Large portions of the Indus and Tsangpo Rivers further east in the Himalaya also follow this structural feature. Having presented evidence for Quaternary deformation, we compare the vertical component of rock displacement in the hanging wall of the main backthrust relative to the magnitude of erosion at similar timescales (Fig. 1), as it is this ratio that will determine the signal of topographic change across the valley. Thrust displacement rates are measured using mapped and dated alluvial and lacustrine terraces, and by documenting displacement of these terraces across faults. Erosion rates are presented using published low temperature thermochronology (Kirstein et al., 2006; 2009) and detrital cosmogenic nuclides (Dortsch et al., 2011a; Munack et al., 2014; Dietsch et al., 2014). In addition, the distribution of changing erosion rates in response to thrust displacement is inferred regionally through an analysis of river channel steepness of catchments that drain into the Indus valley. Sedimentological evidence for valley damming in response to fault movement, and for the migration of the main river channel is also presented. The integration of structural, topographic, erosional and sedimentological data enables us to present a model that characterises the surface process interactions during the topographic deformation of river catchments by thrust faulting within active mountain ranges; our chronological data provides the timescales for these processes.

2. Regional background

The Indus River

of Ladakh flows northwestward (Fig. 2). between the highly deformed Cretaceous to Miocene sediments of the Indus Molasse which are thrust northeastwards against the relatively undeformed Cretaceous and Palaeogene Ladakh Batholith complex (Figs 2 and 3). The Indus Molasse records sedimentation in a forearc basin that evolved into an intramontaine basin following continental collision (Garzanti and Van Haver, 1988; Searle et al., 1990; Sinclair and Jaffey, 2001). The Ladakh Batholith forms part of the Gangdese Batholith complex at the boundary between the northern mountains of the Himalaya and the Tibetan Plateau. It represents the magmatic arc prior to continental collision and comprises a succession of granodioritic rocks overlain by a volcanic succession that form the southern wall of the Shyok Valley to the north (Weinberg and Dunlap, 2000).

The Indus Molasse of the Stok Range is intensely deformed with fold and thrust structures verging to the northeast and southwest. At the boundary with the Ladakh Batholith, the Cretaceous succession locally onlaps the margin of the batholith (Van Haver, 1984), but the main topographic boundary is defined by a thrust fault that carries steeply tilted Miocene molasse successions in its hanging wall over Quaternary alluvial fan deposits; we term this the Stok Thrust (Fig. 3) which laterally correlates to the Great Counter Thrust further east (Murphy and Yin, 2003). The bulk of deformation of the Indus Molasse has occurred since deposition of the youngest sediments around 20 Ma (Sinclair and Jaffey, 2001). The extent to which deformation has continued since this time has not been documented.

The Ladakh Batholith contains crystallisation ages ranging from ca. 103 to 47 Ma (Honegger et al., 1982; Weinberg and Dunlap, 2000), and is overlain by a volcanic succession along its northern margin which is tilted steeply northeastwards (Weinberg et al., 2000). This rotation is thought to have occurred in the hanging wall of a thrust fault that dips northeastward under the batholith, and which was active during early Miocene times (Kirstein et al., 2006); this structure is comparable to the Gangdese Thrust near Lhasa (Yin et al.,1994). Thermochronological analyses using apatite and zircon U-Th/He dating and apatite fission track dating indicates rapid cooling of ~25°C/Myr around 22 Ma followed by a deceleration to rates <3.5°C/Myr since then (Kirstein et al., 2006).

Detrital cosmogenic ^{10}Be analysis across the Ladakh batholith indicate erosion rates of approximately 0.04-0.09 m kyr^{-1} for the main tributaries on the northeastern side and 0.02-0.05 m kyr^{-1} on the southwestern side (Dortsch et al., 2011a; Munack et al., 2014). Smaller, side tributaries on the southwestern side of the batholith record rates as low as 0.008 m kyr^{-1} (Dietsch et al., 2014); these represent the slowest rates recorded from the Himalaya. These measurements average over tens of thousands of years, and record an asymmetry in erosion rates associated with greater degrees of glaciation on the northern side of the Ladakh batholith driving glacial headwall erosion and migration of the drainage divide towards the southeast over this time period (Jamieson et al., 2004; Dortsch et al., 2011). Small (~1km long) glaciers are still present at the drainage divide around 5500m elevation, with significant glacial erosion having occurred down to approximately 4700m on the southwestern side of the batholith (Hobley et al., 2010). Dating of boulders on moraines in the Ladakh region has demonstrated multiple glaciations recorded in this region, with the oldest significant glaciation being approximately 80$\pm$20 Ka (Owen et al., 2006; Dortsch et al., 2013). On the southwestern margin of the Indus valley, erosion rates from the Indus Molasse successions of the Stok Range are faster than on the batholith with ^{10}Be concentrations implying millennial erosion rates of 0.07-0.09 m kyr^{-1} (Munack et al., 2014).

In the Leh region of the valley, the northwesterly flowing Indus River is bound by large alluvial fans draining the Indus Molasse from the southwest. These fans appear to force the present river channel to bank up against the interfluve ridges of the batholith to the northeast (Fig. 3). A terrace containing evidence of lake sedimentation forms the distal margin of these alluvial fans (Fig. 4), and other terraces in the valley testify to a history of damming of the Indus river (Burgisser et al., 1982; Fort, 1983; Phartiyal et al., 2005; Blöthe et al., 2014). The presence of broad regions of alluvium in the lower reaches of the tributaries draining the batholith (geomorphic domain 3 of Hobley et al., 2010, 2011) encouraged Jamieson et al. (2004) to suggest that an asymmetry in deformation and erosion across the Indus Valley has resulted in a northeastward translation of the valley over the batholith. However, evidence for ongoing structural deformation and relative displacement of the Indus Molasse has not been recorded (Dortsch et al., 2011), and is therefore a key focus of this study. As the valley is traced northwestward from the village of Phey, so the river's course cuts a large gorge into the deformed molasse, and the long profile exhibits a broad steepening downstream of the alluviated reach in the Leh valley (Jamieson et al., 2004).

3. Evidence for Quaternary shortening

3.1 Fan Terrace data. Geomorphic fill terraces usually record abandoned floodplain surfaces that parallel the modern river channel, and can usually be correlated across the landscape, and so can be used to assess evidence of ongoing deformation since formation (e.g. Lavé and Avouac, 2001; Pazzaglia and Brandon, 2001; Wegmann and Pazzaglia, 2009). The terraces in the Leh region of the Indus Valley represent the abrupt downslope termination of alluvial fan surfaces into a 20-80m succession of bedded sandstones and laminated siltstones that record floodplain and shoreline settings around the edge of ancient lakes; this sedimentological transition is associated with a geomorphic break recording the approximate coastline of the palaeo-lake. In order to distinguish these features from classic fill terraces (e.g. Wegmann and Pazzaglia, 2009), we refer to these as ‘fan terraces’. One of the best documented sections through a fan terrace succession is in the Spituk region near Leh where radiocarbon dates yield ages from ca. 51 to 31 ka (Phartiyal et al., 2005). Several terraces successions also contain extensive soft sediment deformation that has been interpreted as a record of seismicity throughout the region (Phartiyal and Sharma, 2009). We mapped two terrace fill successions around the northwestern part of the Leh Valley that could be correlated across the two sides of the valley (Fig. 4). Field mapping of terrace successions using a laser range finder was supported by Google Earth satellite imagery and the one arc second Shuttle Radar Tomography Mission digital elevation model (DEM) with a 30m horizontal resolution. The top surface of the higher fan terrace (T1) is at an average elevation of around 3250m and represents the dissected remnant of an alluvial fan with lacustrine sediments at downslope break in topography (Figs 4 and 5). A lower fan terrace succession is capped by a surface (T2) at around 3200m elevation and is evident throughout the region. This level forms the break of slope between alluvial fans that drain the Stok range and the modern Indus River floodplain in the Leh valley (Fig. 4).

The sedimentology of the T1 infill is best exposed around Spituk (Fig. 4) where at least 50m of silts, sands and gravels are present (see supplementary figure 1) recording lake sedimentation (Burgisser et al., 1982; Phartiyal et al., 2005). The lower portions of the section are dominated by coarse grained, fining-upward event beds delivered from marginal deltaic feeder systems. This thick succession underlying the T1 surface can be traced at the same elevation downstream for at least 10 km (Fig. 4b). The lower T2 infill is exposed in the cliffs on the southwest side of the valley opposite Spituk. This succession is approximately 20m thick and dominated by poorly bedded coarse gravels and breccias typical of alluvial fan sedimentation. Approximately 2 to 4 m below the fan surface is a succession of well bedded, fine to medium sands with some planar lamination, and some evidence of rootlets, grass blades, shells and other organic material. There is also a 40 cm unit of finely laminated siltstones, similar to the lacustrine deposits of the T1 fill (see supplementary figure 2). This interval is interpreted as an episode of lacustrine and marginal floodplain sedimentation that defined the base-level for the alluvial fans that drain the Stok Range (Fig. 4a). In contrast to the T1 fill succession, downstream tracing of the T2 terrace fill demonstrates a reduction in elevation that is parallel, but approximately 25 m above the modern Indus River.

As the Indus River continues downstream to the northwest, so it changes course from flowing at the boundary between the Indus Molasse and the Ladakh Batholith to flowing within, and along the strike of the Indus Molasse where it forms a steep gorge (Figs 4 and 5a). Either side of this gorge, the two terraces fills are clearly visible, with the T1 fill characterised by light, cream coloured lake sediments, and T2 with a more pink tone where the sediment forms a bench in the gorge. Near to the turning for the Markha Valley, the T1 fan terrace is deformed by thrusting, folding and extensive irregular soft sediment deformation (Fig. 6). At the southwestern extent of the terrace, it is overthrust by the Indus Molasse on a fault dipping at 37° to the southwest. Thinly bedded alluvium is folded into a broad syncline in the footwall of the fault with a wavelength of approximately 200 m (unit 1, fig 6 and 7). Within this lower succession are meter-scale thrust faults and folds that are draped by overlying beds and hence are syn-depositional. An unconformity divides this folded succession into two, recording a phase of erosion and renewed sedimentation prior to the final phase of folding. These folded alluvial sediments are truncated by a structureless breccia with meter-scale blocks of the Indus Molasse that is interpreted as a surficial debris flow deposit that ranges from 2-5 m thick (unit 2, figs 6 and 7). This debris flow is draped by finely laminated pale siltstones that are interpreted as lake deposits (unit 3, figs 6 and 7). These siltstones are capped by gravels of the abandoned T1 alluvial fan surface (unit 4, figs 6 and 7); this surface has since been dissected by a dense network of modern river channels (Fig. 5b). In comparison, the lower T2 fill is undeformed.

These exposures are interpreted as a record of syn-depositional thrust faulting that caused progressive deformation of Indus valley alluvium, culminating in the formation of a rock slide or debris flow that subsequently dammed the valley leading to lake formation. Folding and intraformational unconformities in the footwall of the thrust indicate that this was fault propagation folding with associated growth strata (e.g. Suppe et al., 1992). A minimum calculation for the amount of shortening across the structure needs to include both the fault offset and the footwall folding of the alluvium. A conservative estimate for the total shortening is 9.8 m (Fig. 6). Soft-sediment deformation has been recognised elsewhere in this T1 terrace fill as well as a fault offset between the batholith granites and lake sediments near Spituk (Phartiyal and Sharma, 2009).

The exposures in the region of Spituk, near Leh (Fig. 4) are dated using four radiocarbon ages that range from ~50.8 ± 5 ka at the base to ~31.0 ± 0.7 ka near the top (Fig. 3; Phartiyal et al., 2005). Given the significance of thrust shortening of the T1 terrace, we chose to date the deformed T1 terrace sediments near the Markha valley using optically stimulated luminescence (OSL) on quartz, and to compare this against the range of radiocarbon ages at Spituk, and against new ages for the other terraces.

3.1.1 OSL Methodology (see supplementary material for full description) - We collected 20 samples of medium- and fine-grained sand and silt layers for optically-stimulated luminescence (OSL) dating of quartz grains, and most samples were derived from units that were interbedded with coarse-grained or conglomeratic deposits of fluvial and alluvial fan origin. Other deposits that were sampled record lacustrine environments, and reworked horizons overlying mass flow deposits. Samples were collected in copper tubes (2.5 cm diameter, 12 cm long) that were tapped into the target deposits parallel to the stratigraphic orientation. The tubes were sealed with black tape to avoid light penetration and to minimise any moisture loss within the tubes. At least 2 cm of sediment from both ends of each tube were used for dosimetry measurements, and the remaining material was used for dating. Analysis of luminescence behaviour, dose rate estimation and age calculations were conducted at University of St Andrews using the protocol outlined in King et al. (2013). The analytical details and results (with tables and figures) are presented in the Data Repository. Only 17 of the 20 samples were dated, and two ages are based on a low number of aliquots (Zansk2011-1 and Nimmu2011-1).

3.1.2 OSL results – **T1 terrace fill**: The four samples from the deformed T1 terrace succession near the Markha junction generated ages, in ascending stratigraphic order of 35.6 ± 2.7, 73.0 ± 0.7, 40.0 ± 5.2 and 77.2 ± 11.7 ka (Fig. 6); given the observed stratal sequence, these cannot all represent true depositional ages. Having confidently correlated the T1 succession from Spituk to the Markha junction (Fig. 4b), we would expect the ages to fall within the time interval of 50.8 ± 5.4 to 31.0 ± 0.7 ka based on the radiocarbon ages at Spituk (Phartiyal et al., 2005). In order to be confident of the OSL correlation to the radiocarbon ages, we also ran a sample from the top of the Spituk T1 succession and obtained an age of 27.5 ± 3.0 ka. Consequently our interpretation of the ages at the Markha junction locality is that the two ages that are significantly older than the radiocarbon age bracket record age overestimation. Inheriting older ages is common in fluvial systems where sediment grains were not fully exposed during transport and deposition meaning that their luminescence ‘clocks’ had not been reset (incomplete bleaching – Wallinga, 2002). This is particularly common where coarse sands were deposited by short-lived, turbid flows and mass flows that are typical in alluvial fan settings.

T2 terrace fill: The T2 terrace fill was sampled on the opposite side of the valley from Spituk at the margins of the large alluvial fans that dip gently northward into the Indus Valley (Fig. 4). The samples were taken approximately 20m above the modern floodplain and comprised sands and gravels with finer grained intervals (supplementary figure 2). The three samples (Dung2011-01,02 and 03) yield ages of 22.0 ± 1.3, 19.1 ± 0.7 and 11.7 ± 0.7 ka (see supplementary table 3). Similar ages ranging between 22.0 ±1.3 and 8.8 ± 0.8 ka from terrace levels downstream near Nimu and Basgo suggest that this was a period of widespread sediment aggradation throughout this part of the Indus Valley.

3.1.3 Horizontal displacement rates - Based on the stratigraphic location of the T1 Markha junction samples (Fig. 6), deformation of this succession must have started during accumulation of the alluvial deposits of unit 1 with ages of 35.6 ± 2.7 ka; in order to convey conservative estimates of shortening rates we use the oldest possible age for the lowest stratigraphic unit of 38.3 ka. Based on the total horizontal displacement (folding and faulting) since deposition of unit 1 of 9.8 m, and the oldest age for the deformed alluvium of 38.3 ka, we estimate a mean shortening rate from that time to the present of at least 0.25 m kyr^{-1}.

3.2 Topographic expression of shortening. Whether the activity on the Stok Thrust was localised or regional is significant in the context of its impact on orogenic topography. Therefore, we use fluvial topography to test the lateral extent of thrust activity in the Indus Molasse (e.g. Kirby and Whipple, 2012).

It has been recognised for over a century that erosion rates in bedrock channels should increase with increasing channel gradient and water discharge (e.g., Gilbert, 1889). If other factors are equal, for example rock hardness or local uplift rates, channel gradients should decrease as discharge (or its proxy, drainage area) increases, and so any topographic analysis that uses channel gradients as a proxy for erosion rates must take into account drainage area. A number of authors have used a scaling relationship, $S = k_s A^{-\theta}$, where S is the topographic slope, k_s is a steepness index regressed from slope and area data, A is the drainage area and and θ describes the rate of change of slope or concavity of the long river profile, to explore changes in erosion rates along bedrock channels (Wobus et al., 2006). If θ is set to a fixed value, the steepness index k_s becomes a normalized steepness index, k_{sn}, and this index has been applied to a number of regions of active tectonics; importantly, it can identify differential rock uplift fields that are bordered by faults that have not been historically active, and so aid seismic hazard awareness (Kirby and Whipple, 2012). However, the selection of θ and identification of reaches with statistically different values of k_{sn} can be difficult with noisy slope and area data.

Our topographic analysis of river long profiles normalises for drainage area by integrating drainage area over flow distance. This method, first suggested by Royden et al. (2000), produces a transformed coordinate, χ (chi), which has dimensions of length (Perron and Royden, 2012). The elevation of the channel can then be plotted against the χ coordinate, and the gradient of the transformed profile in χ-elevation space provides a steepness indicator that can be used to compare channel segments with different drainage areas.

The transformed coordinate is calculated with

$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x)}\right)^{m/n} dx, \qquad (1)$$

where x [dimensions length, dimensions henceforth denoted as [L]ength and [T]ime in square brackets is the flow distance from the outlet, x_b [L] is the flow distance at the outlet, A [L^2] is the drainage area, A_0 [L^2] is a reference drainage area introduced to ensure the integrand is dimensionless, and m and n are empirical constants, and where $-m/n = \theta$.

The choice of the integrand in equation (1) is informed by a simple model of channel incision called the stream power model (e.g., Howard and Kerby 1983, Whipple and Tucker, 1999)

$$E = KA^m S^n, \qquad (2)$$

where E [L T^{-1}] is the erosion rate, S [dimensionless] is the slope and K is an erodability coefficient with dimensions that depend on the exponent m. Royden and Perron (2013) demonstrated that in landscapes where channel incision could be described by equation (2), changes in erosion rates at the base of channels would result in upstream migrating "patches" or segments of constant slope in chi-elevation space, given constant bedrock erodibility and local uplift rates. These segments can be described by:

$$z(x) = B_\chi + \left(\frac{E}{K(A_0)^m}\right)^{1/n} \chi, \qquad (3)$$

where $z(x)$ [L] is elevation. Equation (3) is a linear equation with an intercept of B_χ [L] and a slope [dimensionless] that Mudd et al. (2014) called M_χ, or the gradient in χ-elevation space:

$$M_\chi = \left(\frac{E}{K(A_0)^m}\right)^{1/n} \qquad (4)$$

Other models have been proposed for channel incision, including those that incorporate the role of sediment supply (Sklar and Dietrich, 1998) and erosion thresholds (e.g., Snyder et al., 2003). However, even if the stream power incision model is an imperfect description of channel incision (Lague, 2014), Gasparini and Brandon (2011) demonstrated that equation (2) works as an approximation of the proposed incision models. At a minimum, both M_χ and k_{sn} can still be calculated and allow a qualitative comparison of the steepness of channel segments relative to their upstream area from different parts of the channel network. Both chi-analysis and the normalized steepness index (k_{sn}) have been found to correlate well with erosion rates in the Yamuna River which is a basin to the south of Ladakh (Scherler et al., 2013).

We use a method developed by Mudd et al. (2014) to determine the most likely locations of channel segments. This method tests all possible contiguous segments in a channel network and selects the most likely segment transitions using the Aikake Information Criterion (*AIC*; Aikake,1981), which is a statistical technique that rewards goodness-of-fit while at the same time penalizing over fitting. Mudd et al. (2014) used both field examples and numerical models to show the method could distinguish channel segments of varying erosion rates via detection of varying M_χ values; their results followed the analytical work of Royden and Perron (2013) demonstrating that the chi method could distinguish varying erosion rates in transient landscapes. Changes in M_χ may be due to factors other than changing erosion rates, for example changes in channel erodibility could force changes in M_χ. The Mudd et al. (2014) method is agnostic with regards to the cause of changing M_χ values, it simply finds segments with different M_χ values that may be differentiated statistically.

To calculate both segments and M_χ values, the transformation of equation (1) requires values for both A_0 and m/n to be selected. The reference drainage area simply scales χ, so it changes the absolute of M_χ but not relative values. The *m/n* ratio is, on the other hand, determined statistically. We follow the method of Devrani et al (2015) in which target basins are selected (in our case 12 basins, 6 in the Ladakh batholith and 6 in the Molasse) and in each basin 250 sensitivity analyses were run in each of the 12 basins to determine the range of *m/n* ratios in each basin and to determine a regional *m/n* value to be used in calculating M_χ values.

In the Ladakh region, it has been previously noted that river concavity (i.e. *m/n*) varies in relation to the degree of upstream glaciation (Hobley et al., 2010) which suggests local channel slopes are not a simple function of rock uplift or lithology. In order to avoid the influence of glaciation, we selected those catchments where moraines, valley widening and channel slope reduction due to glacial erosion were absent; these being the characteristics of the upper glaciated domain of Hobley et al. (2010). Based on 12 of these smaller, non-glaciated catchments we derived a range of concavity values with a mean of 0.4 for both the Indus Molasse and the Ladakh Batholith; i.e. there was no significant difference between them. Once we determined the regional *m/n* ratio, we then applied this to all the river networks in the region to map $M\chi$ values of channels draining into the Indus from both the North and South.

The channel steepness for all rivers across the region demonstrate a high degree of variability (Fig. 8a), particularly within the larger tributaries that drain from the glaciated drainage divide of the Ladakh and Stok ranges. These variable M_χ values link directly to the three geomorphic domains associated with glacial erosion, incision into glacial moraine and alluvial fan growth identified by Hobley et al. (2010). Therefore, these larger catchments were not used for the evaluation of variable erosion rates across the region; we speculate that the variation may be linked to the sediment flux dependent channel incision processes documented in a number of these valleys by Hobley et al. (2011). However, the smaller unglaciated catchments that range from 4 to 18 km in length provide M_χ values that can be compared throughout the region (Fig. 8b).

We compare M_χ values for opposing catchments on either side of the Indus River valley (Fig. 9c), which, due to the proximity of their outlets, have the same local base level (i.e., the Indus River). M_χ values are consistently higher, and more variable, on the southwestern margin of the valley on the Indus Molasse compared to the opposing tributaries that drain the batholith. Within the batholith, the relatively constant M_χ values suggest that there is little spatial variation in local uplift rates, channel erodibility or erosion driven by base level changes; it is also noticeable that there is no change in the channels as they pass across the transition from bedrock to alluvial fan sedimentation. In contrast to the batholith catchments, there is a high degree of variability in the Molasse catchments, which also have higher M_χ values for opposing catchments. There are also changes associated with mapped structures within the Indus Molasse such as the Choksti thrust (Sinclair and Jaffey, 2001).

It is unlikely that the variation in M_χ values in the Molasse has been caused by variations in base level along the Indus because if this were the case the variability in M_χ would be mirrored in the Ladakh batholith. Variability is more likely caused by changes in channel erodibility or changes in local rock uplift rates. Changing drainage areas due to divide migration can also alter M_χ values, but changing drainage area is unlikely to cause discontinuities in middle reaches of channels such as those seen in Figure 9c.

Systematically higher M_χ values in the Molasse again cannot be explained by erosion driven by local base level since channels in the Molasse and the Ladakh batholith both drain into the Indus which sets local base level. Thus the increased M_χ values must be explained by differences in erodibility, erosion rates or changes in drainage area. It seems unlikely that the Molasse has a lower erodibility than the Ladakh batholith given its friable nature in contrast to the crystalline rock north of the Indus.

We then turn our attention to possible structures (i.e. the Stock Thrust) within the Molasse, which might lead to either increased local relative uplift (i.e., increased uplift relative to the Ladakh batholith) or changes in drainage area. If the Molasse is being thrust towards the northeast, leading to motion of the drainage divide relative to the Indus, it would truncate drainage area at the base of the catchment at the point of the thrust fault but would not affect drainage area upstream. This is because the entire catchment would be advected to the north. On the other hand, if there were internal deformation within the Molasse, in which drainage areas were systematically declining within the Molasse, then according to equation (1), χ would increase while elevation remained relatively constant, leading to a decrease in M_χ, which is the opposite of what we observe. A vertical component of thrusting would lead to increases in channel gradients and erosion rates across any faults, which is consistent with our observation of greater M_χ values in the Molasse. This is corroborated by data from cosmogenic ^{10}Be (section 4.2).

We therefore find the most likely interpretation of the contrasting M_χ values between the Molasse and the Ladakh batholith is the presence of at least one active thrust fault, within the Molasse. We propose that the northeastward vergent Stok Thrust, as identified in the deformed terraces (Fig. 6) can be traced as an active structure along the range front at the head of the large alluvial fans that feed the Indus Valley (Fig. 8b), and that there is likely to be additional active displacement across other structures within the Indus Molasse such as the Choksti Thrust (van Haver, 1984; Sinclair and Jaffey, 2001).

3.3 **Sedimentary evidence of northward migration of Indus river channel**. In addition to the deformed terraces and steepened river profiles, there is sedimentary evidence to indicate that the course of the main Indus river channel has migrated north-eastward through time.

The dissection of the T1 fan surface described previously (Fig. 5b) exposes the internal stratigraphy of the fan, which reveals a unit comprising coarse boulder conglomerates with very well-rounded clasts up to 1.5 m diameter, comprising multiple lithologies but with granodiorite from the Ladakh Range being dominant. Boulders and pebbles show strong imbrication indicating flow towards the northwest (i.e. parallel and downstream with the modern Indus River). Exposures of this boulder conglomerate are seen in isolated locations higher up the fan, approximately 1.2 km from the modern Indus river channel and 120 m higher (Fig. 5c).

Overlying the boulder conglomerate is a poorly structured gravel comprising angular clasts of the Indus Molasse. These gravels are very poorly sorted with some clasts greater than 1m. The vague bedding dips gently down the direction of the dissected fan surface. In the middle of these gravels is a light cream-coloured bedded and laminated siltstone, with interbeds of the gravels.

This upper succession represents deposits of the the ancient alluvial fan interbedded with lake sediments that are traceable into the deformed T1 lake sediments described previously approximately 3.7 km west-northwest from this location as unit 4 (Figs 6 and 7). Underlying the alluvial gravel, the boulder conglomerates must represent the course of the Indus palaeo-channel prior to ca. 50 ka (oldest age of the T1 terrace from Phartiyal et al., 2005). The implication being that the modern Indus River channel has migrated northeastward since ca. 50 Ka.

4. Erosion rates across Indus Valley

Having calculated rates of structural displacement across the Stok Thrust, published erosion rates from the upthrown side of the fault are synthesised in order to evaluate the balance between vertical displacement rates and erosion rates. In addition, these rates are compared to the time equivalent erosion on the opposite side of the Indus valley from the Ladakh Batholith, as the river morphologies suggest lower erosion rates. Published data on bedrock thermochronology and cosmogenic ^{10}Be are presented as a record of long (>10^6 yrs) and short-term (<10^5 yrs)

4.1 Thermochronology. Thermochronology studies the cooling histories of rock samples within the top few kilometres of the earth's surface, which in most mountain ranges can be used as an approximation of erosion rates (Reiners and Brandon, 2010). Apatite fission track and apatite and zircon U-Th/He data have been extensively published from across the Ladakh region, with the majority of the analyses on the Ladakh batholith (e.g. Kirstein et al., 2006; 2009). We integrate these data with published values from the Indus Molasse in the Stok Range (Clift et al., 2002; Sharma and Choubey, 1983).

The age-elevation data from the centre of the Ladakh Batholith as recorded by all three thermochronometers, indicate rapid cooling at around 20 Ma (Kirstein et al., 2006), possibly linked to southward-vergent thrusting of the Batholith. However, the lower elevation, interfluve promontories on the south-western margin of the batholith nearest to the modern Indus River comprise older ages (Fig. 9). For example, the apatite fission track ages range between ca. 35-30 Ma (Kirstein et al., 2009); this increase in age at lower elevations on the southern margin of the batholith remains to be explained.

Published apatite fission track ages from the Indus Molasse in the Zanskar Gorge record central ages of 13.7 ± 3.2 and 13.8 ± 1.9 Ma (Clift et al., 2002). An additional age from further east was reported as being between 7 and 9 Ma (Sharma and Choubey, 1983). Assuming similar geothermal gradients across the Indus Valley, the contrast in ages (Fig. 9b) from the Indus Molasse (ca. 14 Ma) to the southwestern margin of the Ladakh Batholith (ca. 30-35 Ma) and into the core of the batholith (ca. 20 Ma) implies that the long-term erosion rates in the Indus Molasse were at least twice as fast relative to those in the batholith since at least ca. 14 Ma. The absolute erosion rates are difficult to assess due to lack of multiple thermochronometers and vertical profiles, but assuming a geothermal gradient of ~30°/km, and closure temperature of 110° (e.g. Reiners and Brandon, 2012), then the likely erosion rates were of the order of 0.1-0.3 m/kyr. We interpret the higher longer term erosion rates in the Indus Molasse to have resulted from Miocene to recent deformation, and the development of the Stok Range (Sinclair and Jaffey, 2001).

4.2 Cosmogenic nuclides. Concentrations of cosmogenically induced radionuclides such as ^{10}Be and ^{26}Al in quartz are routinely used for dating the period of exposure of a rock at the surface (Lal, 1991). Applications include dating boulders on glacial moraines (e.g. Brown et al., 1991) and fluvial bedrock strath terraces (e.g. Burbank et al., 1996). Additionally, cosmogenic radionuclides measured from quartz-sand in river catchments can be used to estimate catchment-wide erosion rates (Lal and Arnold, 1985; Brown et al., 1995). This method fills the gap between traditional erosion estimates determined from measured river sediment loads (Schaller et al., 2001) and long timescales approximated using thermochronology.

Analysis of cosmogenic ^{10}Be from sediment across the Ladakh batholith has demonstrated erosion rates ranging from ~ 0.02-0.08 m kyr^{-1} (Dortsch et al., 2011). These rates are slow compared to the mean for the Himalaya mountain range as a whole which is ~ 1.0 m kyr^{-1} (Lupker et al., 2012). The catchments along the southern side of the Ladakh Batholith have calculated mean erosion rates of between ~ 0.02 m kyr^{-1} and 0.04 m kyr^{-1} (Dortsch et al., 2011; Munack et al., 2014; Fig. 10). Further detrital ^{10}Be from the Stok Range record erosion rates of 0.07 to 0.09 m kyr^{-1} (Munack et al., 2014); this supports the fission track thermochonology by indicating erosion rates of the Indus Molasse that are approximately twice as fast as those over the batholith on the opposing side of the Indus Valley (Fig. 9b).

5. Interpretation of results (Fig.11)

The above results confirm that structural shortening is taking place across the present Indus Valley, with horizontal displacement rates of at least 0.25 m kyr^{-1}, which represents just a small fraction (<2%) of the total shortening across the Himalaya in this region. The deformation of the Stok Range is generating a steepening of river channels with higher erosion rates and a higher sediment flux into the Indus Valley relative to the opposing tributaries that drain the Ladakh Batholith. The steepened river channels enable the field of high rock uplift relative to the Indus River valley to be mapped to the east of the observed thrust, indicating that the Stok thrust has been active along the north-eastern margin of the mountain front.

Whether the horizontal displacement rate across the Indus Valley is sufficient to permanently offset the drainage divides depends on the ability of the erosive processes to counter the topographic displacement induced by the deformation. In bedrock channel networks, the erosive processes are driven by the propagation of the steepened channel as a knickzone up to the head of the catchments and its impact on hillslopes. In geometric terms, a river catchment's ability to fully recover its form during shortening across a thrust fault can be simplified to a ratio of the vertical rock displacement rate (V_v; this being displacement relative to the footwall block) versus the erosion rate in the hanging wall of the thrust (Fig. 1). The vertical rock displacement rate is a function of the horizontal displacement rate (V_h) times the combined tangents of the dip of the thrust (β) and the topographic slope (α). The Stok Thrust has a measured dip at the surface of 37°, and the mean surface slope of the Stok Range from ridge crest to valley floor is approximately 8° (Fig. 9a). Therefore, a horizontal displacement rate of 0.25 m kyr^{-1} equates to a vertical displacement rate of ~0.22 m kyr^{-1}.

The catchments that drain the hanging wall of the Stok Thrust are sourced from the Indus Molasse where the erosion rates measured from ^{10}Be concentrations range from ~0.07 to 0.09 m kyr^{-1}. This implies that more than half of the vertical, and proportionately half the horizontal component of displacement on the fault is converted into a topographic displacement at the surface, the rest being eroded. The implication is that the drainage divide that forms the spine of the Stok Range must be migrating towards the Indus River at approximately half the rate of horizontal displacement on the Stok Thrust, equating to approximately 0.13 m kyr^{-1}. However, given the presence of knickzones up the Stok Range catchments (Fig. 9c), the ^{10}Be concentrations are likely recording a mixture of higher erosion rates (lower ^{10}Be concentrations) below the knickzones, and lower above (higher ^{10}Be concentrations), where the kinematic wave of accelerated incision has not reached. For this additional reason, it is possible that the calculation for divide migration is an under-estimate, and that the true value is likely to lie somewhere between 0.13 m kyr^{-1} and the horizontal fault displacement rate of 0.25 m kyr^{-1}.

Greater fault displacement rates than erosion rates in the hanging wall of the Stok thrust demonstrate that this topographic form is evolving, and that the elevation contrast from outlet to drainage divide across the Stok Range (catchment relief), is likely to be increasing over long timescales. If we assume the elevation of the Indus Valley is constant, then it would suggest that catchment relief is growing at a similar rate to the divide migration rate, i.e. ~0.13 m kyr^{-1}. However, the elevation of the Indus Valley relative to the surrounding tributaries has fluctuated as recorded in the documented alluvial terraces, but the present elevation of the Indus River is up to 100m lower than it was approximately 50 ka (Fig. 4b). Based on this evidence, it is hard to conclude whether the long term elevation of the Indus River channel is rising or falling relative to the deforming Indus Molasse of the Stok Range.

As sediment flux increases with relief and channel steepening, so the alluvial fans that drain into the Indus Valley off the Stok Range must have expanded. The expansion of alluvial fans from this side of the valley has forced the present-day Indus channel to migrate laterally towards the opposing valley margin against the rock promontories of the batholith (Fig. 11). This interpretation is supported by the presence of Indus river boulder conglomerates exposed beneath the present fans that drain the Indus Molasse (Fig. 5b and c). Another consequence of the asymmetry in erosion and sediment flux across the Indus Valley is the aggradation of alluvial fans within the valleys of the Ladakh Batholith. This aggradation has resulted in some isolated hills or inselbergs of granodiorite that once formed parts of interfluve ridges, but are now buried in alluvium and topographically detached from the range.

While this study has focused on the tectonic driver for topographic narrowing of the Indus Valley, it is clear that asymmetry of erosion rates driven by lithology and climate will also influence divide migration. In the case of the Indus Valley, the divide that runs along the Ladakh Batholith has also experienced a strong asymmetry in glacial erosion, with headwall retreat rates of 0.18 to 0.6 m kyr^{-1} in the northeastward facing glaciated catchments (Dortsch et al., 2011). This will have enhanced the signal of valley narrowing through tectonics as documented here. Although not documented, it is possible that a similar process has taken place over the glaciated portions of the Stok Range drainage divide.

An additional consequence of the thrust deformation driving topographic shortening across the valley is the increased susceptibility to damming of the valley (e.g. Burgisser et al., 1982; Blöthe et al., 2014). We have been able to demonstrate that the thickest lacustrine terrace in the Leh Valley was caused by thrust motion at ca.

38 ka on the Stok thrust leading to debris flows and consequent damming of the valley. The younger T2 terrace can also be correlated downstream to similar age deposits which incorporate numerous mass flow deposits (e.g. Blöthe et al., 2014). Clearly, the large number of terraces recorded along the Indus Valley, are likely to have similar mechanisms of formation involving debris flows and landslides, and hence see this as a characteristic of actively convergent longitudinal valleys such as the Indus.

Here, we have documented the structural, topographic and surface process response to slow horizontal displacements across a single valley. We would expect similar processes to take place simultaneously across numerous structurally defined, strike parallel (longitudinal) valleys in any large mountain range. In the Himalaya, rivers such as the Tsangpo and Shyok, and the upper reaches of the Kosi, Sutlej and Karnali all run parallel to structures that may be actively modifying catchment form in a similar way to the Indus case presented here. This is particularly relevant where active shortening occurs in regions of relatively low erosion rates as in the lee of the Himalaya.

6. Conclusions

1) Through OSL dating and analysis of Quaternary terraces in the Indus Valley, Ladakh, it is demonstrated that the south-westwardly dipping Stok Thrust, which represents a lateral continuation of the Great Counter Thrust in the Himalaya, was active from ca. 38 ka, resulting in approximately 10 m of shortening. The displacement on this structure resulted in debris flows blocking the valley, and the formation of a lake in this part of the Indus Valley.

2) Mapping of river channel steepness using the chi parameter in the hanging wall of the Stok thrust indicates that its recent activity was laterally traceable at least 80 km south eastward along the valley. The variably steepened channels of the Stok range contrast with the relatively steady, lower gradient (normalised for area) channels that drain the Ladakh Batholith on the opposing side of the Indus Valley.

3) Erosion rates as recorded by low temperature thermochronology and detrital ^{10}Be concentrations from river sediment are approximately twice as fast over the Stok Range (up to 0.09 m kyr^{-1}) relative to the Ladakh Batholith (up to 0.04 m kyr^{-1}).

4) Deposits of the Indus river channel buried beneath the alluvial fans sourced from the Indus Molasse testify to the northeastward migration of the present river channel. The interpreted mechanism is that relatively high sediment yield from the Stok Range has forced the course of the present channel against the opposing valley margin formed by the batholith. In addition, the high sediment yield has forced fluvial base-levels to rise over the batholith, blanketing the interfluve bedrock ridges with alluvium.

5) The contrast in the vertical rock displacement rate of the hanging-wall of the Stok Thrust (~0.22 m kyr^{-1}) versus the erosion rate (<0.09 m kyr^{-1}) requires a change in surface topography. The fact that approximately half of the vertical rock displacement is countered by erosion implies that approximately half of the structural shortening is recorded as topographic convergence of drainage divides across the valley. This recorded deformation of the Indus river valley at rates of ~0.1 m kyr^{-1} represents the first documentation of the processes and consequent topographic and sedimentological record of narrowing of a major longitudinal river valley in an active mountain range.

References

Akaike, H.,1981, Likelihood of a model and information criteria: Journal of econometrics, v.16(1), p. 3-14.

Bishop, P., 1995. Drainage rearrangement by river capture, beheading and diversion. Progress in physical geography, v.19(4), pp.449-473.

Blöthe, J. H., Munack, H., Korup, O., Fülling, A., Garzanti, E., Resentini, A., and Kubik, P. W., 2014, Late Quaternary valley infill and dissection in the Indus River, western Tibetan Plateau margin: Quaternary Science Reviews, 94, 102-119.

Brown, E. T., Edmond, J. M., Raisbeck, G. M., Yiou, F., Kurz, M. D., and Brook, E. J.,1991, Examination of surface exposure ages of Antarctic moraines usingin situ^{10}Be and^{26}Al: Geochimica et Cosmochimica Acta, 55(8), 2269-2283.

Brown, E. T., Stallard, R. F., Larsen, M. C., Raisbeck, G. M., and Yiou, F.,1995, Denudation rates determined from the accumulation of in situ-produced^{10}Be in the Luquillo experimental forest, Puerto Rico: Earth and Planetary Science Letters, 129(1), 193-202.

Brozović, N., Burbank, D. W., and Meigs, A. J., 1997, Climatic limits on landscape development in the northwestern Himalaya: Science, v. 276(5312), p. 571-574.

Burbank, D., Meigs, A. and Brozović, N., 1996, Interactions of growing folds and coeval depositional systems: Basin Research v. 8.3, p. 199-223.

Burbank, D. W., Leland, J., Fielding, E., Anderson, R. S., Brozovic, N., Reid, M. R., and Duncan, C. ,1996, Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas: Nature, 379(6565), 505-510.

Bürgisser, H.M., Gansser, A., and Pika, J., 1982, Late glacial lake sediments of the Indus Valley area, northwestern Himalayas: Eclogae Geologicae Helvetiae, v. 75, no. 1, p. 51–63.

Castelltort, S., Goren, L., Willett, S. D., Champagnac, J. D., Herman, F., and Braun, J., 2012, River drainage patterns in the New Zealand Alps primarily controlled by plate tectonic strain: Nature Geoscience, v. 5(10), p. 744-748.

Champel, B., van der Beek, P., Mugnier, J.L. and Leturmy, P., 2002. Growth and lateral propagation of fault-related folds in the Siwaliks of western Nepal: Rates, mechanisms, and geomorphic signature. Journal of Geophysical Research: Solid Earth, 107(B6).

Clift, P., Carter, A., Krol, M., and Kirby, E., 2002, Constraints on India-Eurasia collision in the Arabian Sea region taken from the Indus Group, Ladakh Himalaya, India, in Clift, P., et al., eds., The tectonic and climatic evolution of the Arabian Sea region: Geological Society [London] Special Publication 195, p. 97–116.

Dahlen, F. A. 1990, Critical taper model of fold-and-thrust belts and accretionary wedges: Annual Review of Earth and Planetary Sciences, v.18, p. 55.

Devrani, R., Singh, V., Mudd, S.M., Sinclair, H.D., 2015, Prediction of flash flood hazard impact from Himalayan river profiles: Geophysical. Research Letters 42, 5888-5894, doi:10.1002/2015GL063784

Dietsch, C., Dortsch, J. M., Reynout, S. A., Owen, L. A., and Caffee, M. W., 2014, Very slow erosion rates and landscape preservation across the southwestern slope of the Ladakh Range, India: Earth Surface Process and Landforms, doi: 10.1002/esp.3640

Dortch, J.M, Owen, L.A., Schoenbohm, L, M. and Caffee, M., 2011a, Asymmetrical erosion and morphological development of the central Ladakh Range, northern India: Geomorphology, v. 135, 0. 167-1809,

Dortch, J.M., Dietsch, C., Owen, L.A., Caffee, M. and Ruppert, K., 2011b, Episodic fluvial incision of rivers and rock uplift in the Himalaya and Transhimalaya, Journal of the Geological Society, London, v. 168, p. 783-804. Doi: 10.1144.0016-76492009-158

Dortsch, J. M., Owen, L., and Caffee, M. W., 2013, Timing and climatic drivers for glaciation across semi-arid western Himalaya-Tibetan orogeny: Quaternary Science Reviews, v. 78, p. 188-208.

Fort, M., 1983, Geomorphological observations in the Ladakh area (Himalayas): Quaternary evolution and present dynamics, in Gupta, V.J., ed., Stratigraphy and Structure of Kashmir and Ladakh, Himalaya: New Delhi, Hindustan Publishing, p. 39–58.

Garzanti, E., and Van Haver, T., 1988, The Indus clastics: forearc basin sedimentation in the Ladakh Himalaya (India): Sedimentary Geology, v.59(3), p. 237-249.

Gasparini, N.M. and Brandon, M.T., 2011, A generalized power law approximation for fluvial incision of bedrock channels: Journal of Geophysical Research-Earth Surface, 116, F02020. doi:10.1029/2009JF001655

Gilbert, G.K., 1877, Geology of the Henry Mountains, USGS Unnumbered Series, Monograph. Government Printing Office, Washington, D.C., 160p.

Gupta, S., 1997, Himalayan drainage patterns and the origin of fluvial megafans in the Ganges foreland basin: Geology v. 25.1, p. 11-14.

Hallet, B., & Molnar, P., 2001, Distorted drainage basins as markers of crustal strain east of the Himalaya: Journal of Geophysical Research: Solid Earth (1978–2012), v. 106(B7), p. 13697-13709.

Herman, F., and Braun, J., 2006, Fluvial response to horizontal shortening and glaciations: A study in the Southern Alps of New Zealand: Journal of Geophysical Research: Earth Surface, v. 111(F1).

Hobley, D. E.J, Sinclair, H. D., and Cowie, P. A., 2010, Processes, rates, and time scales of fluvial response in an ancient postglacial landscape of the northwest Indian Himalaya: Geological Society of America Bulletin, v.122(9-10), p. 1569-1584.

Hobley, D.E.J., Sinclair, H.D., Mudd, S.M., and Cowie, P.A., 2011, Field calibration of sediment flux dependent river incision: Journal of Geophysical Research, v. 116, F04017, doi: 10.1029/2010JF001935.

Hodges, K. V., Wobus, C., Ruhl, K., Schildgen, T., and Whipple, K., 2004, Quaternary deformation, river steepening, and heavy precipitation at the front of the Higher Himalayan ranges: Earth and Planetary science letters, v. 220(3), p.379-389.

Honegger, K., Dietrich, V., Frank, W., Gansser, A., Thoni, M. and Trommsdorff, V., 1982, Magmatism and metamorphism in the Ladakh Himalayas (the Indus-Tsangpo suture zone): Earth and Planetary Science Letters, v. 60, p. 253-292.

Howard, A. D., and Kerby, G. ,1983, Channel changes in badlands: Geological Society of America Bulletin, 94(6), 739-752.

Howard, A.D., Dietrich, W.E. and Seidl, M.A., 1994, Modeling fluvial erosion on regional to continental scales. Journal of Geophysical Research: Solid Earth v. 99.B7, p. 13971-13986.

Jamieson, S. S. R., Sinclair, H. D., Kirstein, L. A., and Purves, R. S., 2004, Tectonic forcing of longitudinal valleys in the Himalaya: morphological analysis of the Ladakh Batholith, North India: Geomorphology, v.58(1), p.49-65.

King, G.E., Robinson, R.A.J. and Finch, A.A., 2013. Apparent OSL ages of modern deposits from Fåbergstølsdalen, Norway: implications for sampling glacial sediments: Journal of Quaternary Science, 28(7): 673-682.

Kirby, E., and Whipple, K. X., 2012, Expression of active tectonics in erosional landscapes: Journal of Structural Geology, v. 44, p. 54-75.

Kirstein, L. A., Sinclair, H., Stuart, F. M., and Dobson, K., 2006, Rapid early Miocene exhumation of the Ladakh batholith, western Himalaya: Geology, v. 34(12), p. 1049-1052.

Kirstein, L. A., Foeken, J. P. T., Van Der Beek, P., Stuart, F. M., and Phillips, R. J., 2009, Cenozoic unroofing history of the Ladakh Batholith, western Himalaya, constrained by thermochronology and numerical modelling: Journal of the Geological Society, 166(4), 667-678.

Koons, P. O., 1995, Modeling the topographic evolution of collisional belts: Annual Reviews of Earth and Planetary Sciences, v. 23.1, p. 375-408.

Lague, D., 2014. The stream power river incision model: evidence, theory and beyond: Earth Surface Process and Landforms 39, 38–61. doi:10.1002/esp.3462.

Lal, D. and Arnold, J.R., 1985. Tracing quartz through the environment: Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences v. 94, p. 1–5.

Lal, D. ,1991, Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models: Earth and Planetary Science Letters, 104(2), 424-439.

Lavé, J., and Avouac, J.P., 2001, Fluvial incision and tectonic uplift across the Himalayas of central Nepal: Journal of Geophysical Research, v. 106, no. B11, p. 26,561–26,591, doi: 10.1029/2001JB000359.

Lupker, M., Blard, P. H., Lavé, J., France-Lanord, C., Leanni, L., Puchol, N., and Bourlès, D. 2012. ^{10}Be-derived Himalayan denudation rates and sediment budgets in the Ganga basin: Earth and Planetary Science Letters, v. 333, p. 146-156.

Miller, S. R., and Slingerland, R. L. 2006. Topographic advection on fault-bend folds: Inheritance of valley positions and the formation of wind gaps. Geology, v. 34(9), p. 769-772.

Miller, S.R., Slingerland, R.L. and Kirby, E., 2007. Characteristics of steady state fluvial topography above fault-bend folds. Journal of Geophysical Research: Earth Surface, v. 112(F4).

Mudd, S.M., Furbish, D.J., 2005, Lateral migration of hillcrests in response to channel incision in soil-mantled landscapes: Journal of Geophysical Research-Earth Surface, 110, F04026. doi:10.1029/2005JF000313.

Mudd, S., Attal, M., Milodowski, D., Grieve, S.W.D., Valters, D., 2014, A statistical framework to quantify spatial variation in channel gradients using the integral method of channel profile analysis: Journal of Geophysical Research-Earth Surface, 119, 138–152. doi: 10.1002/2013JF002981.

Munack, H., Korup, O., Resentini, A., Limonta, M., Garzanti, E., Blöthe, J. H., and Kubik, P. W., 2014, Postglacial denudation of western Tibetan Plateau margin outpaced by long-term exhumation: Geological Society of America Bulletin, 126 (11-12), 1580-1594. doi: 10.1130/B30979.1

Murphy, M. A., and Yin, A. , 2003, Structural evolution and sequence of thrusting in the Tethyan fold-thrust belt and Indus-Yalu suture zone, southwest Tibet: Geological Society of America Bulletin, v.115(1), p.21-34.

Oberlander, T. 1965. The Zagros streams: a new interpretation of transverse drainage in an orogenic zone (No. 1): Distributed by Syracuse University Press.

Owen, L. A., Caffee, M. W., Bovard, K. R., Finkel, R. C., and Sharma, M. C., 2006, Terrestrial cosmogenic nuclide surface exposure dating of the oldest glacial successions in the Himalayan orogen: Ladakh Range, northern India: Geological Society of America Bulletin, v. 118(3-4), p. 383-392.

Pazzaglia, F. J., and Brandon, M.T., 2001, A fluvial record of long-term steady-state uplift and erosion across the Cascadia forearc high, western Washington State: American Journal of Science. v. 301, 4-5 , p. 385-431.Perron, J. T., and Royden, L., 2012, An integral approach to bedrock river profile analysis: Earth Surface Processes and Landforms. v. 38, 6, p. 570-576. DOI: 10.1002/esp.3302

Phartiyal, B., Sharma, A., Upadhyay, R., and Sinha, A.K., 2005, Quaternary geology, tectonics and distribution of palaeo- and present fluvio/glaciolacustrine deposits in Ladakh, NW Indian Himalaya—A study based on field observations: Geomorphology, v. 65, no. 3–4, p. 241–256, doi: 10.1016/j.geomorph.2004.09.004.

Phartiyal, B., and Sharma, A. (2009). Soft-sediment deformation structures in the Late Quaternary sediments of Ladakh: Evidence for multiple phases of seismic tremors in the North western Himalayan Region: Journal of Asian Earth Sciences, v.34(6), p.761-770.

Reiners, P. and Brandon, M. 2006. Using Thermochronology to Understand Orogenic Erosion: Annual Review on Earth and Planetary Sciences v. 34, p. 419-466.

Perron, J. T., & Royden, L., 2013, An integral approach to bedrock river profile analysis: Earth Surface Processes and Landforms, v.38(6), p.570-576.

Schaller, M., Von Blanckenburg, F., Hovius, N., and Kubik, P. W. (2001). Large-scale erosion rates from in situ-produced cosmogenic nuclides in European river sediments: Earth and Planetary Science Letters, v.188(3), p.441-458.

Scherler, D., Bookhagen, B., and Strecker, M. R. (2014). Tectonic control on 10Be-derived erosion rates in the Garhwal Himalaya, India: Journal of Geophysical Research: Earth Surface, v. 119(2), p. 83-105.

Searle, M. P., Pickering, K. T., and Cooper, D. J. W., 1990, Restoration and evolution of the intermontane Indus molasse basin, Ladakh Himalaya, India: Tectonophysics, v.174(3), p.301-314.

Seeber, L., and Gornitz, V.,1983, River profiles along the Himalayan arc as indicators of active tectonics: Tectonophysics, 92(4), 335-367.

Sharma, K.K and Choubey, V.M., 1983, Petrology, geochemistry and geochronology of the southern margin of the Ladakh Batholith between Upshi and Choumatang. In: Thakur, V. C. and Sharma, K. K., eds., Geology of the indus Suture Zone of Ladakh. Wadia Institute of Himalayan Geology, Dehra Dun, India, p. 41-60.

Sinclair, H. D., and Jaffey, N., 2001, Sedimentology of the Indus Group, Ladakh, northern India: implications for the timing of initiation of the palaeo-Indus River: Journal of the Geological Society of London v. 158.1, p. 151-162.

Sinclair, H. D., Gibson, M., Naylor, M., and Morris, R. G., 2005, Asymmetric growth of the Pyrenees revealed through measurement and modeling of orogenic fluxes: American Journal of Science, v. 305(5), p. 369-406.

Sinclair, H.D. and Walcott, R., in review, Catchment shape in the Himalaya; the role for tectonics: Geology.

Sklar, L., and Dietrich, W. E., 1998, River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply. Rivers over rock: fluvial processes in bedrock channels, p. 237-260.

Snyder, N. P., Whipple, K. X., Tucker, G. E., and Merritts, D. J., 2003, Importance of a stochastic distribution of floods and erosion thresholds in the bedrock river incision problem: Journal of Geophysical Research: Solid Earth, v. 108(B2), p.1978–2012.

Suppe, J., Chou, G. T., and Hook, S. C., 1992, Rates of folding and faulting determined from growth strata. In: Thrust tectonics (pp. 105-121). Springer Netherlands.

Van Haver, T., 1984, Etude stratigraphique, sedimentologique et structurale d'un bassin d'avant arc: exemple du bassin de l'Indus,. Ladakh, Himalaya. Thesis Univ. Grenoble, Grenoble p. 204.

Wallinga, J., 2002, On the detection of OSL age overestimation using single-aliquot techniques: Geochronometria, v. 21(1), p. 17-26.

Whipple, K. X. and Tucker, G. E., 1999, Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs: Journal of Geophysical Research, Solid Earth 104.B8 17661-17674.

Wegmann, K.W. and Pazzaglia, F.J., 2009. Late Quaternary fluvial terraces of the Romagna and Marche Apennines, Italy: climatic, lithologic, and tectonic controls on terrace genesis in an active orogen. Quaternary Science Reviews, v. 28(1), pp.137-165.

Weinberg, R.F., Dunlap,W.J. and Whitehouse, M. 2000. New field, structural and geochronological data from the Shyok and Nubra valleys, northern Ladakh; linking Kohistan to Tibet. In: Khan, M.A., Treloar, P.J., Searle, M.P. and Jan, M.Q. (eds.)

Tectonics of the Nanga Parbat syntaxis and the western Himalaya: Geological Society of London, v.170, p. 253-275.

Weinberg, R.F. and Dunlap,W.J. 2000. Growth and deformation of the Ladakh batholith, northwest Himalayas: Implications for timing of continental collision and origin of calcalklaine batholiths: The Journal of Geology, v.108, p. 303-320.

Willett, S. D., Slingerland, R., and Hovius, N., 2001, Uplift, shortening, and steady state topography in active mountain belts: American Journal of Science, 301(4-5), 455-485.

Willett, S. D., McCoy, S. W., Perron, J. T., Goren, L., and Chen, C. Y., 2014, Dynamic reorganization of river basins: Science, v. 343(6175), p. 1248765.

Wobus, C., Whipple, K. X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K. and Sheehan, D., 2006, Tectonics from topography: Procedures, promise, and pitfalls. Special Papers-Geological Society of America, v. 398, p.55.

Wobus, C. W., Crosby, B. T. and Whipple, K.X., 2006, Hanging valleys in fluvial systems: Controls on occurrence and implications for landscape evolution: Journal of Geophysical Research, Earth Surface v. 111.F2.

Yin, A., Harrison, T.M., Ryerson, F.J., Chen, W., Kidd, W.S.F., and Copeland, P., 1994, Tertiary structural evolution of the Gangdese thrust system, southeastern Tibet: Journal of Geophysical Research, v. 99, p. 18,175–18,201, doi: 10.1029/ 94JB00504.

FIGURE CAPTIONS

Figure 1. Cartoon illustrating the mechanics of rock displacement by a thrust fault bounding a longitudinal valley and the erosional response required to sustain a steady state topography. A. A schematic cross-section across the Indus Valley. B. A geometric representation of the Indus Valley enabling the application of trigonometric

relationships between main paramters. For a horizontal displacement rate across the fault (V_h) the vertical displacement rate (V_v) at any point in the hanging wall is a function of the slope of the thrust plane (β) and the mean topographic slope (α). In order to retain a steady state topography following shortening, the vertical rock displacement must be countered by an equal amount of erosion (grey shaded area). For a topographic narrowing of the valley to occur, the vertical displacement rate must be greater than the mean erosion rate on similar timescales in order to sustain a component of the horizontal displacement and translation of the drainage divide..

Figure 2A. Regional setting of study. The cross-section in 2B and the region in figure 3 are shown. **B.** Regional cross-section through the north-western Himalaya showing the geological setting of the upper Indus River valley. The Stok Thrust (fig. 3) represents the major northeastward-vergent backthrust immediately southwest of the Ladakh Batholith; this thrust is comparable to the Great Counter Thrust recorded further east (e.g. Murphy and Yin, 2003).

Figure 3. Hillshade image of the Indus Valley in the Ladakh region with principal geological features shown. The Ladakh Batholith is highlighted by a lighter transparency. The drainage divides that define the margins of the Indus Valley are shown with thick dashed lines. White stars are the location for published apatite fission track samples (Kirstein et al., 2006; 2009; Clift et al., 2002). The location of figures 3a and 7 are shown by dotted and dashed lines respectively.

Figure 4A. Detailed hillshade image of the lower Leh valley using 30m one arc second SRTM data. White areas record exposures of the upper T1 terrace fill, and dark areas record exposures of the lower T2 terrace fill. The reconstructed lake level at the time of the end T1 terrace fill is shown as a dotted line. Dated ages used in this analysis are shown in light boxes. Normal text from the eastern exposures near Spituk show radiocarbon ages from Phartiyal et al. (2005). Italicised numbers show ages generated from OSL analysis in this study. Underlined age in the west represents a ^{10}Be exposure age from Dortsch et al. (2011). **B.** Lateral tracing of the T1 (circles) and T2 (triangles) terrace fills from Spituk in the east to the Markha valley junction in the west. These data were generated using a laser range finder plotted relative to the height of the modern river (squares).

Figure 5A. View up the Indus River Valley from the junction with the Markha Valley. Two terraces are evident at this location; a lower bench representing the younger T2 terrace marked by dots and characterised by a pinky cream siltstone. The upper T1 terrace contains a lacustrine deposit (labelled) and forms the dipping fan surface in the middle ground above this deposit. The far mountains are part of the Ladakh Batholith. **B**. View over the dissected T1 terrace surface immediately east of the Markha valley junction. Section shown in C is located. **C.** Topographic cross-section across Stok Thrust showing exposures of conglomerates deposited by an older Indus river channel draped by modern alluvial fan sediments sourced from the Indus Molasse.

Figure 6. Deformed Quaternary terrace sediments near Markha Valley junction (Fig. 4). **A**. Photographic montage of T1 terrace fill exposed along the road track (note circled small car for scale). The four stratigraphic units that make up the terrace are described in the text. **B**. Drawing of photograph in A showing location of OSL samples (dots) and ages. Circled numbers refer to stratigraphic units labelled in A. **C**. Projected section through the terrace fill enabling total shortening to be calculated, each component of faulting and folding is accounted for with a length in meters. The lower unit 1 comprising bedded alluvial gravels contains an unconformity recording the progressive motion on the thrust during this interval. The last stage of deformation is truncated by the debris flow (unit 2) which is then draped by lacustrine sediments (unit 3). Figure 7A is a measured sedimentary section through this succession.

Figure 7. Sedimentary sections through the T1 terrace at the Markha junction and Spituk. A. Sedimentary section through the T1 fill exposures near the Markha Valley junction illustrated in figure 6. The succession records the impact of thrust activity on the Stok Thrust which caused progressive deformation of unit 1 and the ultimate emplacement of a mass flow unit of figure 2 that resulted in damming of the valley and lake formation (unit 3). The two starred ages are the OSL ages that were complimentary to the radiocarbon ages from Spituk (Phartiyal et al., 2005). B. Approximately time equivalent sedimentation at the Spituk site recording subaqueous deposition dominated by laminated lake sediments pounctuated by event beds that record hyperpycnal discharge from the mountain rivers. The black pentagons show sites of radiocarbon ages (Phartiyal et al., 2005).

Figure 8. Analysis of river steepness using the chi-parameter for catchments draining both sides of the Indus Valley. **A**. $M\chi$ values for all catchments showing highest values in glaciated upper reaches and lowest in alluvial stretches near valley floor, calculated using $\theta = 0.4$. **B**. Catchments selected where there is no impact of glaciers, and where channel gradient is solely a function of fluvial processes. $M\chi$ values for these are plotted in figure 9c where the data from each numbered catchment is identified. Black line indicates Stok Thrust overthrusting to northwest. Dashed lines represent drainage divides.

Figure 9. Analysis of the asymmetry of erosion and topography plotted as a transect across the Indus valley **A**. Maximum, minimum and median lines of elevation across the Indus Valley with location of main thrust faults. Values are mean values from a 10km wide swath (see supplementary figure 3 for location of transect). **B.** Apatite fission track ages (black circles) projected onto line of swath transect in A. Location of samples shown in figure 2 (ages from Kirstein et al., 2006; 2009; Clift et al., 2002). Grey boxes show the range of values of erosion rates calculated from the detrital ^{10}Be cosmogenic nuclide analysis from Dortsch et al., (2011) and Munack et al., (2014). Numbers of catchments measured are given in each of the boxes. **C**. $M\chi$ values plotted for each of the catchments in figure 8b against their distance from the Indus valley floor. Overall, figure demonstrates faster erosion rates, younger fission track ages and steeper and more irregular river channels over the Indus Molasse of the Stok Range.

Figure 10. Detrital ^{10}Be derived erosion rates for tributary catchments draining into the Indus River from Dortsch et al., 2011 and Munack et al., 2014. Data demonstrate clear asymmetry of erosion rates with higher values from catchments draining the Stok Range (values in ovals) versus those draining the Ladakh Batholith (values in rectangles).

Figure 11. Interpreted evolution of the Indus Valley near Leh since Miocene times. **A**. A broad valley with the early formation of the Stok Range and a stable Ladakh Batholith with slow erosion rates as derived from the thermochronology (Kirstein et al., 2006). Dotted relief shows position of mountain range in B. **B**. Relative uplift of the Stok Range due to shortening generates erosion and sediment flux that outpaces the flux from the batholith leading to the migration of the Indus Channel

towards the northwest. **C**. Around 35 ka motion on the Stok Thrust generates mass flows off the Stok range that cause a damming of the Indus Valley leading to formation of a large lake with deltas feeding in from the margins. **D**. Present configuration with high relief and high gradient catchments over the Indus Molasse with high sediment flux forcing the Indus river channel against the batholith. Sediment aggradation out paces river incision in the lower reaches of the batholith leading to sediment accumulation of the lower interfluve ridges and local isolation to form inselbergs. Terrace remnants record episodic damming of valley due to thrust activity.